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Brief communication: Threshold not probability. The conceptual difference between ID thresholds for landslide initiation and IDF curves

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Abstract. Intensity-duration (ID) thresholds are used to identify rainfall conditions likely to initiate landslides. They consider the average rain intensity observed over the entire length (called duration) of user-defined events. Intensity-duration-frequency (IDF) curves assign a probability to the intensity of precipitation observed over fixed-length temporal windows (also called durations). As the term duration refers to different concepts, ID thresholds and IDF curves cannot be compared directly, and should better not be plotted in one figure, and IDF curves should not be used to quantify the exceedance probability of ID thresholds.

1 Introduction

Regional early warning systems for shallow landslides and debris flows are often based on rainfall intensity-duration (ID) thresholds (Guzzetti et al., 2008; Segoni et al., 2018). These thresholds are derived from landslide archives and rainfall observations with the aim of separating triggering and non-triggering events on the basis of their duration and average intensity (Leonarduzzi et al., 2017). IDF curves are the standard tool to calculate the annual exceedance probability of extreme rainfall intensities over a duration of interest (Kottegoda and Rosso, 2008). It follows that a seemingly natural way to quantify the annual exceedance probability of the rainfall causing landslides or debris flows is to calculate the return period of the intensity of ID thresholds using intensity-duration-frequency (IDF) curves. Indeed, IDF curves have been used to discuss the probability of ID thresholds, including works by the authors of this communication (e.g., Frattini et al., 2009; Destro et al., 2017; Bogaard and Greco, 2018). Here, we highlight an important conceptual difference between the *duration* used in ID thresholds and the *duration* used in IDF curves that has been overlooked by the landslide literature so far. We provide a real-world example and discuss the implications for the interpretation of shallow landslide and debris flow initiation.

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2 Intensity-duration thresholds

Rainfall thresholds are rainfall conditions that, when exceeded, are likely to initiate landslides or debris flows (Guzzetti et al., 2008). Because rainfall is the main trigger for these hazards, rainfall thresholds are among the most widely used tools to forecast the occurrence of landslides and debris flows on the regional scale. Following pioneering work by Caine (1980), the intensity I and the total length of the rain event D began to be used to determine the triggering conditions. Therefore, the *duration* D in this ID space is defined as the total length of the wet period (that is, a user-defined event) that leads to the triggering, and the intensity I refers to the average rain intensity observed during this period. Although landslides are triggered by periods of high intensities that occur within rainfall events (D'Odorico et al., 2005; Moreno et al., 2025), the entire length of the events is typically used to build ID thresholds because in most cases the exact moment of triggering is not known. This approach requires an objective definition of rainfall events (Melillo et al., 2015), although subjective choices remain necessary in this context, as the user needs to define the criteria to separate rainfall events. In addition, rainfall records are often not available at hourly resolutions nor in close range of the landslide (Marra et al., 2016; Marra, 2019), which makes the events separation dependent also on these aspects. Different separation criteria would unavoidably lead to different definitions of the events, with different intensities and durations associated with the initiation of landslides. Due to the wide range of scales spanned by precipitation variability, ID thresholds often take the form of power laws (e.g., Caine, 1980, and the subsequent literature). Several approaches can be used to define these thresholds, including frequentist (Brunetti et al., 2010) and Bayesian methods (Berti et al., 2012), trained on triggering or non-triggering events only or triggering and non-triggering events together (Guzzetti et al., 2008; Peres and Cancelliere, 2021; Leonarduzzi et al., 2017).

3 Precipitation intensity-duration-frequency curves

Intensity-duration-frequency curves are a mathematical relationship among the rainfall intensity, the duration, and the annual frequency of exceedance (Koutsoyiannis et al., 1998). Intensity-duration-frequency curves are the most common tool used in hydrology and water resource engineering to quantify the annual exceedance probability (or frequency) of precipitation. Owing to the wide range of scales explored by precipitation variability, a fundamental parameter in the definition of precipitation probability is the temporal scale, that is defined as the time window of interest. For example this can be defined based on the typical response time of a hydrologic system, or on the typical time scales of the precipitation process of interest. This temporal window is usually called duration and the traditional symbol is D, but, to avoid misconceptions, in this communication we will use the symbol W. The *duration* of IDF curves, therefore, is a temporal running window of fixed length W. IDF are obtained by collecting the highest rainfall intensities observed any year over the time windows of interest. To do so, usually a running window of the desired length is moved across the timeseries and the largest values are extracted. Extreme value distributions are then used to describe these maxima, and intensities corresponding to an assigned cumulative probability are extracted for the required duration. A relationship is then estimated between the given intensities and the durations. Following simple scaling and multi-scaling arguments rooted in fractal theory, IDF curves are often described using scale invariance formulations, which,

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similarly to ID thresholds, take the form of power laws when observed across the temporal scale (Burlando and Rosso, 1996; Langousis and Veneziano, 2007).

4 Conceptual difference between ID thresholds and IDF curves

From the definition of ID thresholds and IDF curves it is clear that the time intervals over which the intensities of rainfall are examined in the two cases are different, although the term used to define them is the same. In fact, duration refers to the total length of an arbitrarily defined rain event D, on the one hand, and to a fixed-length temporal running window W, on the other. The use of the same term for two conceptually different quantities, together with the common double-logarithmic transformation used in the plots, led to misunderstanding of these concepts and misinterpretation of the results.

For a given rainfall event, such as the ones of interest for ID thresholds, the intensity I of IDF curves may refer to any window of length W within the event, with $W = D$ being only one of the possible choices (Tsunetaka, 2021). Indeed, precipitation events are characterized by different return periods at different temporal windows (Bezak et al., 2016; Cache et al., 2025). In a univariate framework, the return period T^* of a rainfall event can reasonably be defined as the maximum among the return periods T_W associated with all possible temporal scales $W \leq D$: $T^* = \max(T_W)$. For example, Marra et al. (2020) showed that once independence is granted, this definition allows one to directly link the statistics of the event maxima to the statistics of the annual maxima, thereby removing the problem of defining rainfall events for quantifying probability. It follows that the length of the user-defined rainfall event D does not necessarily coincide with the temporal window W^* over which rainfall is the most severe (the equality $W^* = D$ only holds in very peculiar cases). Even more crucially, the duration D explored in ID thresholds drastically depends on how rain events are defined. Although several methods are available for objectively define triggering rain events (e.g. Melillo et al., 2015), they all necessarily rely on user-defined parameters.

It is therefore erroneous to quantify the return period T_D of a given intensity I in the ID space of the ID thresholds using probabilities estimated from the IW space of the IDF curves. Since it is always $T_D \leq T^*$, this erroneous approach causes a systematic underestimate of the severity of the triggering rainfall, leading to numerous false alarms when the information is used in real-time early warning systems. In fact, it is much more likely to exceed the ID threshold while the event is ongoing than once the event is over. These false alarms add to the ones caused by systematic sampling of rainfall away from the location of the triggering landslide and by the use of coarse temporal resolution rainfall data (e.g, Marra et al., 2016; Marra, 2019). This same misconception has led to the conceptual error of thinking that long-duration rainfall (frequently up to 100 hours or more) triggers shallow landslides, while, sometimes, it is a high-intensity interval that occurs at favorable preconditions that causes the triggering (Bogaard and Greco, 2018).

5 Real-world example

We use data from 12 storms that triggered 133 debris flows in the eastern Italian Alps during 2005-2014. They constitute ∼40% of all the debris flows recorded in the area in this period (Nikolopoulos et al., 2014). High-quality weather radar observations

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with resolutions of 1 km and 5 minutes are available for these events from Marra et al. (2014). We refer to this study for details on the weather radar correction procedures and on the quality of the derived time series. IDF curves for the area are available from Borga et al. (2005), which derived them using a scaling-invariant approach (see Kottegoda and Rosso, 2008).

For each debris flow, we extracted the precipitation time series observed by the radar over the triggering location. This allows us to overcome the sampling limitations of the rain gauges (Marra et al., 2016). We derived the total length D of the precipitation event and the average precipitation intensity I observed over this time interval (duration concept of ID thresholds). We then examined the maximum intensity observed over a set of running windows of lengths W of 5, 10, 15, 20, 30, 45 minutes and 1, 1.5, 2, 3, 4, 6, 9, 12, 18, 24, 36, 48 hours (duration concept of IDF curves). We identified the window over which the rain was the most severe (i.e., it had the lowest exceedance probability). To do so, we computed the return period T_W associated with the intensity of the rain observed on each of the windows W by inverting equation (7) from Borga et al. (2005) and we identified the window W^* in which the largest return period T^* was observed.

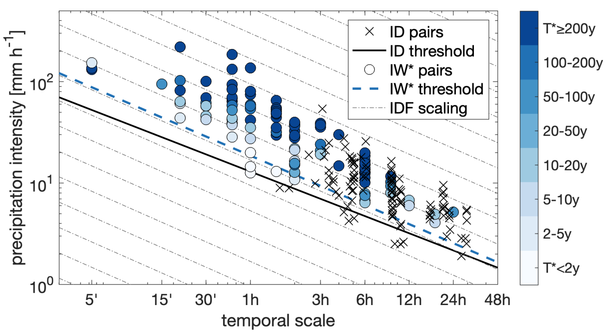

Figure 1. ID pairs of the triggering precipitation time series (black crosses) together with the ID threshold (black solid line). IW* pairs are shown as circles colored according to the return period. The dashed blue line shows the threshold one would obtain using the frequentist method on these IW* pairs. The average scaling invariance of the IDF curves for the region is shown in the background (dashed-dotted lines).

Figure 1 shows the ID pairs corresponding to the 133 debris flows as black crosses, together with the 5% ID threshold obtained using the frequentist method (Brunetti et al., 2010). The IW* pairs are shown as circles, and are colored according to the return period T^*, while the dashed blue line shows the threshold one would obtain using the frequentist method on the IW* pairs. These latter threshold nicely aligns with the regional scaling of extreme rainfall (dashed-dotted lines in the background), solving the apparent difference in the power-law scaling of ID thresholds and IDF curves discussed by Bogaard and Greco (2018). In general, IW* pairs are associated with temporal scales W^* that are always smaller than the duration D of ID pairs (x-axis in Figure 1). In addition, by design, the corresponding intensities are systematically higher. This is a natural consequence of the temporal variability of precipitation (D'Odorico et al., 2005), and implies that what is really important for

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triggering are the rain intensities over time scales that can be much shorter than the total length of the identified rainfall event in combination with the hydrological antecedent conditions. Indeed, for the 133 debris flows examined, the most severe intensities were observed for temporal windows W between 30 minutes and 6 hours (Fig 2a). The severity on these time scales is about an order of magnitude higher than at other windows. Interestingly, these are the time scales of convection, and encompass the scale of individual convective cells, as well as the possible sequence of convective phenomena (Formetta et al., 2022). In fact, the vast majority of debris flows in the area (>90%) are associated with summer convective storms (Nikolopoulos et al., 2015).

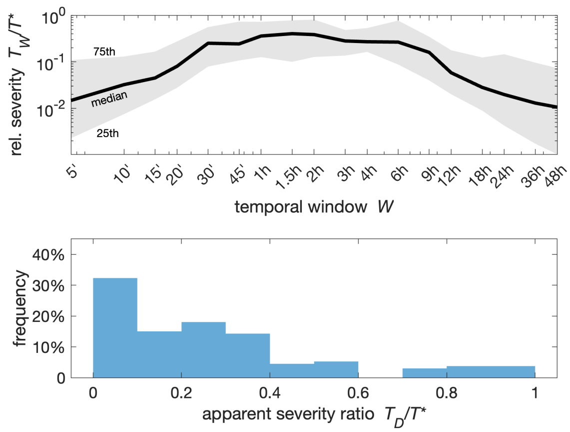

Figure 2. (a) Relative severity of the triggering precipitation for varying temporal window W. The relative severity is computed as the ratio between the return period at the time scale W, T_W, and the maximum return period T^*. The solid line and shaded areas represent the median and inter-quartile range across the 133 debris flows. (b) Apparent severity of the triggering precipitation obtained as the ratio between the return period of the precipitation over the entire storm length D, T_D, and the maximum return period T^*.

We then quantified how much the severity of the triggering precipitation is underestimated when using the entire length of the storm D to calculate the return period T_D. Fig. 2b shows the ratio between the precipitation return period T_D calculated for the intensity observed over the entire length of the storm D and the maximum return period T^* of the event. In ~85% of the cases, the return period estimated over the entire length of the storm is less than half than the maximum return period of the triggering precipitation. In about a third of the cases, it is underestimated by more than one order of magnitude. Once again, these differences are induced by the high temporal variability of the triggering precipitation. Indeed, Fig. 3 shows that the typical decorrelation time of the debris-flow triggering precipitation, computed as the lag time at which the autocorrelation drops to e^{-1}, is on the order of 20-45 minutes (median 35 minutes).

6 Conclusions

We highlight the important conceptual difference between intensity-duration (ID) thresholds for landslides initiation and intensity-duration-frequency (IDF) curves used to calculate extreme rainfall probability. The term *duration* in the two refers to

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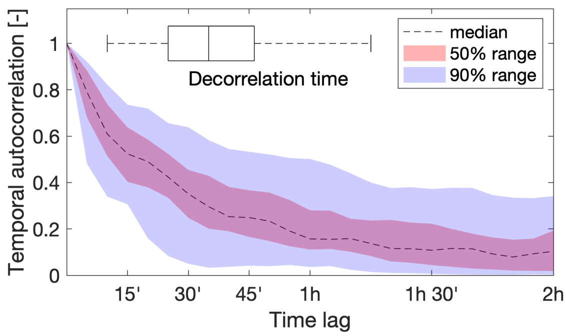

Figure 3. Temporal autocorrelation of the precipitation time series for the 133 debris-flow triggering events.

different concepts: the entire length of the triggering event in the case of ID thresholds, and a fixed-length running window in the case of IDF curves. Interestingly, the highlighted misconception may also explain the apparent difference in the power-law scaling of ID thresholds and IDF curves till 48 hours (e.g., Bogaard and Greco, 2018).

We provide a real-world example of such confusion for the case of debris-flow triggering thresholds in the eastern Italian Alps, showing that the most severe intensities were observed for temporal scales much shorter than the typical length of the triggering events. Estimating the probability of occurrence of these triggering conditions using IDF curves on ID pairs may cause an underestimation of the rainfall return period of even an order of magnitude, leading to abundant false alarms in early warning systems that operate in real time. In addition, representing ID thresholds over too long time scales may result in the wrong concept that shallow landslides and debris flows are triggered by long precipitation events while, in reality, given favorable preconditions, they may be triggered by heavy rain intensities over relatively short time windows (Moreno et al., 2025), the duration of which is related to the physical characteristics of the considered slope or catchment, as already pointed out over twenty years ago by D'Odorico et al. (2005).

In general, IDF curves should not be used to quantify the probability associated with ID thresholds (or ID pairs) and ID thresholds and IDF curves should not be plotted in the same graphs without clearly pointing out the conceptual difference between the two. So far, the highlighted inconsistency was overlooked by the community, leading to erroneous interpretations of probabilities. Some results in the literature may thus be quantitatively inexact.

Code and data availability. Codes and data to reproduce the results and figures of this study are available at https://doi.org/10.5281/zenodo.15845770 (Marra, 2025). The radar data were made available by the Autonomous Province of Bolzano. The parameters of the IDF model were taken from Borga et al. (2005).

Author contributions. FM wrote the manuscript, analysed the data and prepared the figures. All authors contributed to the conceptualization of the study and to revising and structuring the manuscript.

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